

**SINGLE CRYSTAL TUNGSTEN  
PENETRATOR AND METHOD OF MAKING**

This application is a continuation-in-part of U.S. Serial No. 10/046,096, filed January 11, 2002, which was a continuation of International Application No. PCT/US00/19031, filed July 12, 2000, which claimed priority from U.S. Serial No. 60/143,827, filed July 13, 1999, the disclosures of all of which are incorporated herein by reference.

There may be environmental and occupational hazards associated with the manufacture, deployment and use of depleted uranium (DU) as a ballistic penetrator. It would be desirable to have an alternative, benign material having penetration characteristics at least about equal to DU.

When a penetrator interacts with armor, it generates an aerosol and particles which are respirable and which may reach the gas exchange region of the human lung. In addition, penetrator impact fragments are deposited into the soil and can eventually find their way into the human food chain. DU is known to be toxic to the kidney, and it is also theoretically carcinogenic because of its residual radioactivity. Known tungsten heavy alloys, besides being inferior in penetration performance versus DU, contain nickel and cobalt alloying constituents that are also known to be toxic.

As a result of the foregoing, the testing of munitions with DU penetrators is limited to a few testing ranges within the U.S., and essentially, warfighters cannot train with the actual ammunition they will use in wartime because of the severe restrictions placed on training exercises at even these limited testing ranges in the U.S. After DU munitions are used in war (e.g. Desert Storm), a subsequent cleanup effort should be conducted to recover DU from the soil and prevent it from entering a food chain. Stored DU ammunition must be continuously inspected and accounted for during peacetime, introducing a non-productive accountancy requirement to the U.S. logistics chain.

Attempts have heretofore been made to develop polycrystalline tungsten-based composites and tungsten heavy alloys as replacements for DU. Despite developments that led to some increases in strength and toughness, the basic penetration performance of these materials did not significantly improve and did not approach that of DU. These studies demonstrated that penetration performance is not solely a function of strength or ductility.

After much research, it is now believed that material flow and failure mechanisms, not strength and ductility, are key properties in determining penetration performance. As a penetrator strikes armor, a high deformation rate in the penetrator causes heat to be generated. Because there is not enough time to conduct/diffuse this heat away from the deformation area, thermal softening occurs which overcomes the effect of previous hardening mechanisms, such as strain hardening. As a result, gross penetrator deformation occurs in locally softer material, along adiabatic shear bands, and the rapid failure along these adiabatic shear bands allows the penetrator to rapidly shed excess material. This rapid, localized deformation allows material to slough off and thus maintains a small diameter at the penetrator/armor interface. Without such localized shearing, the penetrator would form a large-diameter, blunt-nosed head that is much less effective. For a given value of kinetic energy, the small diameter penetrator will need to move less armor material, and will penetrate farther, than a larger, blunt-nosed penetrator.

The deformation behavior of DU follows the adiabatic shear band phenomenon described above, and the self-sharpening DU penetrator produces a small diameter hole in the armor. Single crystal unalloyed tungsten is also found to exhibit local deformation behavior, along crystalline planes, similar to that of DU. Single crystal unalloyed tungsten, when its [100] axis is parallel to the direction of travel, exhibits penetration capabilities equal to that of DU. Performance in other crystalline orientations, such as [111] or [110], is inferior to the [100] orientation. However, single crystal unalloyed tungsten has a high muzzle-launch failure rate; it appears to lack sufficient strength and ductility to reliably remain intact after launching.

The following criteria have now been developed by U.S. Army TACOM-ARDEC for screening candidate penetrator materials. If a candidate material meets and/or exceeds these screening criteria, it is felt that there is a high assurance that the material will survive muzzle launch. These screening criteria are:

- Ultimate Tensile Strength  $\geq$  180 ksi;
- Tensile Yield Strength  $\geq$  100 ksi; and
- Elongation  $\geq$  12%.

It is an object of the present invention to provide high density penetrators that will meet the foregoing criteria and to provide methods for efficiently and economically fabricating such Penetrator.

### Summary of the Invention

Certain high creep strength, single crystal tungsten alloys have now been developed which have increased strength and ductility compared to that of unalloyed single crystal tungsten; however, in some applications, substantially pure single crystal tungsten may suffice. Tensile tests of one such single crystal tungsten alloy produced the following results:

Ultimate Tensile Strength  $\geq$  200 ksi;

Tensile Yield Strength  $\geq$  100 ksi; and

Elongation  $\geq$  20%.

- 10 Such single crystal tungsten alloys have sufficient strength and ductility to survive muzzle launch and single crystal pure tungsten bodies are also so considered to survive. Such high tungsten alloys contain at least about 90% tungsten, generally between about 90% and about 97%, and alloyed with tungsten will be tantalum, rhenium, niobium, molybdenum or a mixture of two or more of these metals. Hereinafter, for this
- 15 application, reference to "tungsten" by itself should be understood to refer to a metal material that is at least about 90% by weight tungsten.

Also provided are methods for economically and efficiently producing such high density penetrators using CVD. By using an appropriate single crystal substrate and CVD, it has been found that a single crystal body suitable for use as a high density penetrator can be fabricated from tungsten. In addition, a generally closed CVD system is also provided which makes very efficient use of raw materials and minimizes the creation of reaction by-products that would otherwise require processing and/or other clean-up treatment prior to being discarded.

In one particular aspect, the invention provides a high density penetrator designed

- 25 to be propelled from the muzzle of a weapon, which penetrator is generally circular in cross-section, has a diameter of at least 3 mm and a length to diameter ratio of at least about 5 to 1 and comprises a shaped single-crystal alloy body consisting essentially of at least 90% tungsten, said single-crystal body being aligned with [100] orientation with respect to its long axis and being encased in a metal or metal alloy material that has a
- 30 ductility and strength greater than the ductility and strength of said single-crystal body, said encasing material surrounding a head end portion of said single-crystal body and at least substantially the entire length thereof.

In another particular aspect, the invention provides a method for making a single crystal, high density alloy body containing a major amount of tungsten and a minor amount of tantalum, rhenium, niobium and/or molybdenum as an alloying metal, which body is suitable for use as a high density penetrator, said method comprising providing a

5 chamber suitable for carrying out chemical vapor deposition (CVD), locating a single crystal substrate which is stable at a temperature of at least about 800°C within said chamber, introducing (a) tungsten chloride or fluoride vapor or (b) a vapor mixture of chlorides or fluorides of tungsten and said alloying metal into said CVD chamber, with the optional inclusion of H<sub>2</sub>, and heating said single crystal substrate to at least about

10 800° so as to cause a single crystal tungsten alloy body of desired composition to grow upon the exterior surface of said single crystal substrate and create a high-density tungsten alloy body suitable for use as a penetrator.

**Brief Description of the Drawings**

FIGS. 1, 2 and 3 are sectional views of high density penetrators embodying  
15 various features of the invention;

FIG. 4 is a schematic view showing the formation of a high density penetrator using CVD;

FIG. 5 is a view similar to FIG. 4 showing an alternative CVD process embodying various features of the invention; and

20 FIG. 6 is a view similar to FIG. 5 showing another alternative CVD process embodying various features of the invention.

**Detailed Description of the Preferred Embodiment**

Bodies of single crystal material can be formed from tungsten which will have characteristics that will meet desired criteria set down by the United States Army for high  
25 density penetrators that will survive muzzle launch from a weapon. These single crystal materials should contain at least about 90% tungsten, e.g. about 90 to about 100%, preferably contain between about 91% and about 95% tungsten and more preferably contain between about 92% and about 94% tungsten, with one preferred alloy containing about 93% tungsten. Tungsten has a body-centered cubic crystalline structure, and  
30 alloying elements, when included, should either have a body-centered cubic crystal structure or a hexagonal close-packed crystal structure. The remainder of the alloy preferably contains tantalum, rhenium, niobium, molybdenum or a mixture of two or

more of such metals. Although minor amounts of other elements having such a crystal structure can be tolerated, such presence should be minimized so as not to detract from the desired high density of the body. Of the candidates for alloying elements, rhenium has a particularly high density, and tantalum alloys exhibit particularly high strength.

5 Accordingly, tantalum and rhenium are considered to be preferred alloying agencies. As an example, one preferred alloy contains about 93% tungsten and about 7% tantalum. The single crystal body should have a density of at least about 98% of its maximum theoretical density.

The penetrators may have various shapes so long as they are suitable for being  
10 propelled from the muzzle of a weapon, e.g. canons, machine guns and the like. They will normally have a fairly high length to diameter ratio, and they will usually have either an aerodynamically-shaped head or be embodied within a mass that has such a aerodynamically-shaped head as described hereinafter.

FIG. 1 shows a single penetrator or projectile 11 that is made of substantially  
15 homogenous material which is a single crystal tungsten alloy, e.g. 93% W and about 7% Ta. The penetrator 11 has a cylindrical main body 13 and a generally conical head 15. It should have a length/ diameter ratio of at least about 5 to 1, preferably at least about 10 to 1 and more preferably at least about 15 to 1. For example, a penetrator of a larger class may be formed of single crystal material having a diameter of about 1 inch and a  
20 length from about 14 to 24 inches. Smaller size penetrators may have, for example, a diameter of 8.31 mm and a length of 96.4 mm or a diameter of 12.68 mm and a length of 70.5 mm. The single crystal tungsten alloy is formed such that the body-centered cubic crystalline structure is oriented so that the [100] crystalline axis is parallel to the axis of the penetrator 11. Such projectiles are capable of penetrating the armor of tanks and/or  
25 personnel carriers.

It has been found that, in some instances, it may be desirable (see FIG. 2) to encase a single-crystal body 17 in an exterior shell or sheath 19 of a fairly similar dense alloy that has strength and ductility higher than that of the single crystalline body to create an effective penetrator. Examples of suitable materials are those which contain at  
30 least about 90% tungsten and various amounts of nickel, iron and/or cobalt. One that is referred to as WHA contains 93% W, 4.9% Ni and 2.1% Fe; another contains 97.1% W, 1.4% Ni, 0.7% Fe and 0.8% Co. If, for example, it were desired for such a penetrator to have a diameter of about 1 inch, the thickness of the encasing, stronger, more ductile, dense material might be about 0.1 inch (2.5 mm). As illustrated in FIG. 2, the encasing

sheath 19 could completely cover the single crystal body 17 or, if desired, the encasing material could be omitted at the flat tail end of the penetrator.

A further alternative example of a penetrator 21 is shown in FIG. 3 wherein a plurality of uniformly spaced apart rods 23 of single crystal tungsten alloy material are

5 embedded in a matrix 25 that is formed from such dense more ductile tungsten alloy, such as WHA which was discussed above. In such an instance, this plurality of single crystal rods 23 might be individually about 1/8 inch to 1/4 inch (about 3 mm to about 6 mm) in diameter, with the conical head end of the penetrator 21 being formed of WHA or the like. For example, a penetrator 21 of this style might include 44 single crystal,

10 high density, tungsten alloy rods, each about ¼ inch in diameter and 23 inches in length, uniformly spaced within a cylindrical body of WHA having a diameter of about 1 inch. Such an arrangement may have fabrication advantages particularly when the high density single crystal tungsten alloy rods are being grown from fine wire cores.

The single crystal body can be formed using a zone-refining process, as known in

15 this art, in which an electron beam filament carefully locally heats a rod to cause localized melting and then recrystallization. A single crystal seed is located at the bottom of a polycrystalline rod of the desired alloy composition. The electron beam filament initially heats and melts the bottom of the polycrystalline rod where there is contact with the single crystal seed which is oriented with its [100] axis aligned with the

20 long axis of the rod that will constitute the penetrator. The single crystal structure of the seed and its orientation spreads into the molten zone, transforming that portion of the now melted polycrystalline rod into conforming single crystal material. The filament slowly travels up the length of the rod, producing a local molten zone as it travels. This enables the single crystal structure to spread upward, the molten zone transforming the

25 former polycrystalline crystallography into a single crystal having the desired axial orientation. The resultant single crystal material can then be shaped by grinding or other machining operations so as to have the desired penetrator shape, e.g. a solid cylinder having an external head end taper as shown in FIG. 1, plus desired grooves and/or threads and the like.

30 It has been found that high density single crystal material having a desired crystalline axial orientation can also be formed using conventional chemical vapor deposition(CVD) methods. As depicted schematically in FIG. 4, a vaporous (gaseous) mixture of  $\text{WF}_6/\text{TaF}_5/\text{H}_2$  or  $\text{WCl}_6/\text{TaCl}_5$  can be caused to flow over a heated, single-crystal mandrel having a body centered cubic crystalline structure (Mo for example), and

an alloy of tungsten and tantalum can be deposited which will adopt the single crystal structure and the crystalline axial orientation of the mandrel/substrate.

Using a standard quartz chamber or enclosure 31, an alloy is deposited from a mixture 33, for example, having the appropriate proportions of tungsten fluoride,  
5 tantalum fluoride and hydrogen, which may be supplied through an upper entrance 35. By heating a fine wire or thin rod being used as a substrate 37, a single crystal body 39 is formed at a substrate temperature of at least about 800 to 900°C under otherwise standard CVD operating conditions, i.e. flowing the gaseous mixture downward through the coating chamber 31 under reasonably high vacuum conditions (e.g. about 1-20 torr)  
10 and at a rate of about 1.5 µm to about 25 µm per minute. Higher temperatures can be employed and may be preferred depending upon the diameter of the final product that is desired as explained hereinafter. The desired single crystal material grows uniformly radially outward about the surface of the molybdenum wire substrate. Although other body-centered cubic crystalline materials can be used as the substrate 37, single crystal  
15 molybdenum is fairly readily available and is preferred for this reason.

If instead a mixture of tungsten and tantalum chlorides is used together with a higher temperature of about 1200 to about 1300°C and otherwise standard CVD conditions, the desired alloy will be readily deposited without the inclusion of hydrogen. Thus, the inclusion of hydrogen in the gaseous mixture is considered to be optional, and  
20 therefore only a minor amount or no hydrogen may be included. The unreacted chlorides and/or fluorides along with the HF or Cl<sub>2</sub> reaction products are removed from the opposite end 40 of the chamber wherein the coating takes place and must be appropriately reclaimed or disposed of. By appropriately selecting the substrate as a body-centered cubic crystal material with its [100] axis oriented longitudinally, the  
25 desired high density tungsten alloy body 39 having single crystal form and this desired crystalline orientation is obtained.

Both of the foregoing methods are fairly expensive to operate, and it has now been found that a single crystal tungsten alloy material can also be produced using what is being termed a static CVD system and is schematically shown in the accompanying  
30 FIG. 5. In this system, vaporous WF<sub>6</sub>/H<sub>2</sub> or WCl<sub>6</sub> reactants are initially supplied to an otherwise closed reaction chamber 41. The illustrated system is adapted to deposit a tungsten alloy by positioning a solid feedstock 43 of polycrystalline elemental alloy material within the chamber, preferably in surrounding relationship to a centrally located single crystal substrate 45. Within this closed volume, a partial pressure of H<sub>2</sub> (optional)

and, for example, either (a)  $\text{WF}_6$  or  $\text{WF}_6$  and  $\text{TaF}_5$  or (b)  $\text{WCl}_6$  or  $\text{WCl}_6$  and  $\text{TaCl}_5$  vapors are initially provided, as by heating a suitable reservoir 47 containing one or more such reactants 48 to about 80 to 200°C by employing a suitable heater and optionally adding  $\text{H}_2$  (not shown) to the stream which is fed through a valve 50. As previously mentioned,

5 when tungsten chloride is employed, it should not be necessary to add hydrogen although the presence of hydrogen is not felt to detract at all from such CVD. Moreover, it may not be necessary to include a minor amount of the halide of the alloying metal in the vaporous atmosphere that is initially supplied, as this small amount of vapor will account for only a very minor deposition onto the surface of the heated substrate 45, creating a

10  $\text{Cl}_2$  atmosphere that then reacts with the polycrystalline alloy feedstock 43 to thereafter create the desired vaporous alloy composition within the closed chamber 41.

As seen in FIG. 5, the chamber 41 is vertically oriented and designed to have a substrate heater 51 positioned axially above the chamber which would heat, as by resistance heating, a thin wire or rod 45 of molybdenum located centrally, i.e. coaxially, 15 within the chamber. The substrate 45 may have a diameter of about 0.01 inch (0.25 mm) to about 0.032 inch (0.8 mm). Surrounding the substrate 45 upon which the deposition will occur is solid feedstock 43 which may be in the form of a tube of the desired alloy composition or a plurality of individual rods oriented in a circular array about the central substrate. The substrate heater 51 will heat the single crystal substrate 45 to a high 20 temperature as described above, e.g. 900°C to about 1100°C where chlorides are being used. The chamber 41 might be surrounded by a usual resistance or induction heater 53 which might be designed and operated to heat the chamber walls to about 150°C while heating the feedstock material 43 to a temperature which will generally be at least about 100°C lower, and preferably at least about 150°C lower than that of the substrate, e.g. 25 feedstock temperatures may be about 700°C to 900°C. However, higher substrate temperatures may be desirable for reasons set forth hereinafter.

A side entrance 55 is provided in order to initially supply the chamber 41 with the desired gaseous atmosphere. Moreover, an exit conduit 57 is also provided connected via a valve 59 to a pump 61 for evacuating the chamber. Both of these conduits have 30 standard shut-off valves 50, 59.

As an example of operation, the single crystal substrate 45, e.g. Mo wire, and the feedstock 43, e.g. W-Ta alloy, are placed within the chamber 41 and the valve 50 closed. Then, the valve 59 leading to the evacuation pump 61 is opened, and the pump operated to evacuate the chamber to an atmospheric pressure of about 1 torr. Once this low

pressure is achieved, the valve 59 is closed, and the valve 50 is opened allowing tungsten chloride vapor to flow into the reaction chamber from the heated source, which might be at a temperature between about 80°C and about 130°C so that the solid material will have a vapor pressure of about 20 torr. As previously mentioned, a minor amount of hydrogen

5 could be optionally supplied along with the tungsten chloride. When the pressure within the coating chamber reaches about 3-20 torr, the valve 50 is closed, and the heaters 51 and 53 are operated to begin the CVD. As the single crystal mandrel 45, e.g. a thin wire of single crystal Mo, and the polycrystalline tungsten and tantalum feedstock 43 are brought up to operating temperatures, metal alloy from the vaporous chlorides begins

10 depositing causing the single crystal wire to grow radially outward and creating gaseous Cl<sub>2</sub>. The feedstock 43 is heated to an appropriate slightly lower temperature at which a reaction with the metal alloy will occur to form vaporous metal chlorides. RF or resistance heating may be used for either or both heating tasks. For example, the temperature of a polycrystalline W/Ta feedstock alloy may be suitably controlled to

15 provide the desired vaporous atmosphere from which a high density, single crystal body is deposited at the higher temperature of the substrate. WCl<sub>6</sub> and TaCl<sub>5</sub> react at the heated substrate, depositing W and Ta having the desired alloy composition and yielding Cl<sub>2</sub>. The Cl<sub>2</sub> diffuses radially outward from the mandrel and travels to the lower temperature polycrystalline tungsten/tantalum feedstock 43, where it reacts, producing

20 WCl<sub>6</sub> and TaCl<sub>5</sub>.

The operation is allowed to simply continue until the desired diameter single crystal alloy body has been produced. However, to avoid the potential build-up of contamination within the chamber 41 as a result of the possible presence of minute amounts of contaminants within the feedstock material, it may be desired to periodically

25 evacuate the chamber to remove any such contaminants. This can be simply done by momentarily opening the isolation valve 59 and starting the pump 61 to effect such evacuation; thereafter, that valve 59 is closed and the valve 50 to the vapor source 48 is momentarily again opened to replenish the atmosphere as it was initially supplied to start the CVD process. Such evacuation and replenishment might be carried out at any

30 suitable intervals, dependent upon the likelihood of contamination within the feedstock material, e.g. every 30 minutes or 1 hour.

It has been found that, as the diameter of the resultant body being caused to radially grow through CVD substantially exceeds the diameter of the original single crystal wire or rod that serves as the substrate, there is a tendency for the axial orientation

of the newly deposited crystalline material to vary. Generally, this is not a problem until the ratio of the diameter of the single crystal body to the diameter of the original substrate exceeds about 3 or 4 to 1. Because this may oftentimes be the situation, attention has been given to it, and it has been found that carrying out the CVD at a higher 5 temperature, for example about 1600 to about 2200°C, has the effect of annealing out strains that may be induced by such alternative crystalline orientation and assures the growth of the single crystal body having the desired orientation. Accordingly, it may be desirable to employ temperatures in the higher portion of the range of about 800°C to about 2200°C whenever the diameter of the desired resultant product will be more than 10 about five times that of the substrate, in order to assure a uniform resultant product. Even when such higher substrate temperatures are employed, the feedstock temperature is preferably in the range of about 700° to about 900°C.

Once a single crystal body of the desired diameter has been achieved, the equipment is shut down and allowed to slowly cool to ambient temperature. Removal of 15 the body from the chamber 41 and examination shows that it has indeed achieved single crystal structure with the crystalline [100] axis aligned longitudinally of the cylindrical body. Measurement also shows that it is fully dense, having achieved essentially 100% of theoretical maximum density for a body made of 93% tungsten and 7% tantalum, with a minute central molybdenum core.

20 Using this static CVD method, the cost to produce such bodies of high density, single-crystal, tungsten alloys particularly suited for use as high-density penetrators is reduced significantly over either the traditional zone-refining method or the standard CVD method. When employing the standard CVD process, for example, a certain proportion of the metal chlorides or metal fluorides will not react and will be carried out 25 of the reactor as a part of the exhaust system, which then must either be treated to reclaim these reactants or appropriately disposed of. Likewise, there are essentially toxic HF, HCl and/or Cl<sub>2</sub> vapors that exit the reactor that must be handled in an environmentally acceptable manner. It can thus be seen that all this adds to the cost of operation of the standard CVD process whereas, in the static CVD system illustrated in FIG. 5, operation 30 is essentially that of a controlled closed system, and the only waste materials are those which result from the momentary evacuations that are carried out.

A single crystal body can also be produced using the CVD system schematically shown in FIG. 6. In this system, vaporous Cl<sub>2</sub> is supplied to an upstream reaction chamber 65 wherein a bed of tungsten chips 67 are located. Downstream thereof in a

separate section 69 of the chamber is a centrally positioned single-crystal substrate 71. A flow of Cl<sub>2</sub> into the chip bed is provided which forms tungsten chloride vapor in this reaction chamber that is heated to a suitable temperature by employing a suitable tube furnace heater. The tungsten chloride that is formed flows downstream to the CVD

5       chamber 69 via a manifold designed to evenly disperse the gas in a vortex motion. The two-section chamber is vertically oriented, and substrate 71, which may be an electropolished thin rod of single crystal tungsten (100) located centrally, i.e. coaxially, within the chamber section, is heated by induction heating. The substrate 71 may have a diameter of about 0.1 inch (2.5 mm) and be supported in a graphite holder.

10       Two side entrance conduits 73 and 75 are provided at the upstream end in order to supply the chamber with the desired gaseous atmosphere. An exit conduit 77 is connected via a valve 79 to a vacuum pump 81 for evacuating the chamber, and it preferably contains a cold trap 83 and a dry trap 85. The gas conduits 73 and 75 are controlled by mass flow controllers (MFC) which are calibrated to nitrogen, hence all

15       flow settings are relative to this calibration.

As an example of operation, the single-crystal substrate 71, e.g. W rod, and the feedstock 77, e.g., W chips, are placed, respectively, within the sections 69 and 65 of the chamber. Then, the valve 79 leading to the evacuation pump 81 is opened, and the pump is operated to evacuate the chamber to a pressure of about 0.8 torr.

20       The induction heater is controlled to heat the single-crystal tungsten substrate to a temperature of about 1750°C, and the tube furnace that surrounds the upstream section of the reactor is used to heat the bed of tungsten chips to a temperature of about 900°C. A purge flow of hydrogen is supplied through the side conduit 73 at a setting of about 200, i.e. a setting calibrated at 200 standard cubic centimeters per minute (sccm) of nitrogen,

25       and the purge at this temperature is continued for about two hours. The hydrogen MFC is then closed in the side conduit 73, and the substrate is cooled to ambient. The reaction chamber is pumped out by the vacuum pump so as to remove substantially all of the hydrogen while the feedstock bed is maintained at about 900°C. The mandrel is then heated to about 1750°C, while gradually bringing the flow of chlorine gas through the

30       conduit 75 to a setting of 100. The 2-section chamber is maintained at a pressure of about 0.95 torr by controlling the valve 79.

The chlorine setting and this pressure are maintained for about 2 hours, during which time the temperature of the mandrel is slowly raised of to about 1800°C; then the flow of chlorine gas is gradually increased to a setting of about 125, and the temperature

raised to about 1850°C. Both are then so maintained during the second two hour period. At the end of this second two hour period, the chlorine setting is raised to about 150, and the mandrel temperature is raised slowly to about 1900°C via the induction heater. Both are so maintained for the remainder of about 3 hours. At the end of this three hour

5 period, with the mandrel at about 1900°C, the flow of chlorine is raised to a setting of about 175, and such conditions are maintained for about 4 hours. At the end of this 11 hour coating run, the flow of chlorine is halted, and the temperature of the mandrel is cooled to about 750°C over just about two minutes time, where it is maintained for about 1 minute before all power to the induction heater is turned off. Power is also removed

10 from the tube furnace, and the bed of tungsten chips is allowed to cool to ambient. The system is then flushed overnight through a liquid KOH scrubber (not shown) with helium supplied through side conduit 75.

The diameter of the body fairly radially grows through CVD and fairly quickly substantially exceeds the diameter of the original single crystal rod that serves as the

15 substrate. After about 11 hours, the single crystal substrate has grown to about a diameter of 0.3 in (7.6 mm), thus exceeding the diameter of the original substrate by over 300%.

Removal of the tungsten body from the chamber 69 and examination shows that it has indeed achieved single-crystal structure with the crystalline [100] axis aligned longitudinally of the cylindrical body. Analysis also shows that it is fully dense, having

20 achieved essentially 100% of theoretical maximum density for a body made of 100% tungsten.

In certain instances, it may be desirable to have the penetrator include some pyrophoric material, i.e. a pyrophor, which will oxidize and create smoke or fumes that will be indicative that a particular target has indeed been penetrated by breaching its

25 armor, thereby allowing focus to be shifted to another potential target. Suitable pyrophoric materials for this purpose include hafnium, titanium and zirconium. In the case of an otherwise homogenous penetrator, it might be suitable to simply drill out the original molybdenum core and then fill this core with a suitable pyrophor, e.g. hafnium. On the other hand, if a multiple rod penetrator, such as that depicted in FIG. 3, is

30 employed, one or more small rods of hafnium or another pyrophor could be included or discrete particles of a pyrophor might be included as a part of the matrix WHA material used to combine the plurality of single crystal tungsten rods into such a composite penetrator 21.

Although the invention has been described with regard to certain preferred embodiments which constitute the best mode presently known to the inventor, it should be understood that various changes and modifications as would be obvious to one having the ordinary skill in this art, may be made without departing from the invention which is

5 defined by the claims appended hereto. For example, although the discussion of the fabrication processes mention using a feedstock of 93% tungsten and 7% tantalum, all or a part of the tantalum might be substituted by rhenium, and rhenium chloride ( $\text{ReCl}_4$  or  $\text{ReCl}_6$ ) in a minor amount might be included with the vaporous  $\text{WCl}_6$  that is supplied to the chamber. Likewise, in a conventional CVD process, a mixture of hydrogen, tungsten

10 fluoride and rhenium fluorides might be used, or alternatively all or some of the alloying metal could be supplied by niobium fluoride, while still creating a single crystal tungsten alloy penetrator having its [100] axis oriented in the desired direction.

Particular features of the invention are emphasized in the claims which follow.